

PHOTOCONDUCTIVE SWITCH ENHANCEMENTS AND LIFETIME STUDIES FOR USE IN STACKED BLUMLEIN PULSERS*

F. Davanloo, R. Dussart[†], M. C. Iosif, and C. B. Collins

Center for Quantum Electronics, University of Texas at Dallas
P.O. Box 830688, Richardson, TX 75083-0688

F. J. Agee

Air Force Office of Scientific Research, AFOSR/NE
801 N. Randolph St., Arlington, VA 22203-1977

Abstract

Photoconductive switching of the Stacked Blumlein pulsers, developed at the University of Texas at Dallas, currently produces high power, nanosecond pulses with risetimes on the order of 200 ps. The device has a compact geometry and is commutated by a single GaAs switch triggered by a low power laser diode array. This report presents the progress toward improving the high gain switch operation and lifetime in stacked Blumlein pulsers. Feasibility of the use of amorphous diamond to enhance the switch operation and longevity is discussed. Improvement in switch lifetime was demonstrated by coating the triggered face of a GaAs switch cathode with highly adhesive film of amorphous diamond.

I. REVIEW AND STATUS

Stacked Blumlein pulsers consist of several triplate Blumleins charged in parallel at one end and discharged in series at the other end by means of a single switch. In this way, relatively low charging voltages are multiplied to give a high discharge voltage across an arbitrary load. Our recent efforts at the University of Texas at Dallas (UTD), for the first time, resulted in implementation and demonstration of several intense photoconductively switched stacked Blumlein pulsers. Presently, these devices operate with a switch peak power in the range of 50-80 MW and activating laser pulse energies as low as 300 nJ [1,2]. Examinations of output waveforms indicate risetimes as fast as 200 ps. Table I presents the best simultaneous and individual results obtained, to date, by switching the stacked Blumlein pulsers with a high gain GaAs photoconductive semiconductor switch (PCSS). The main objective of our current research is to enlarge the level of understanding and to identify design options which make optimal use of the PCSS for stacked Blumlein based Ultra-Wideband (UWB) sources.

During the avalanche-mode switching of a pulser, the current is concentrated in filaments that extend from the cathode to the anode across the insulating region of the

GaAs switch in a lateral configuration [3]. Carrier recombination results in the emission of characteristic band gap photons in the near infrared region, which can be seen by an infrared viewer.

We have observed these effects in experiments where laser diodes provided trigger photons for the avalanche commutation of the stacked Blumlein pulsers. As soon as the avalanche is initiated, a single filament can be observed which approximately follows the collimated laser beam that was focused in a line from the cathode to the anode. Multiple branching from the avalanche initiation point has also been observed but with much less probability. Filamentary currents with densities of several MA/cm² and diameters of 15-300 μ m passing through a narrow channel can cause switch damage, especially at the contacts points. A greater number of filaments during each cycle of commutation reduce the stress on the switch, thereby increasing its lifetime.

Table 1. Test results obtained by commutation of stacked Blumlein pulsers with the high gain GaAs switches.

Parameters	Simultaneous Results	Individual Results
Switch Voltage	60 kV	100 kV
Switch Current	1.2 kA	2 kA
Pulse Risettime	200 ps	150 ps
R-M-S Jitter	500 ps	200 ps
Optical Trigger Energy	300 nJ	300 nJ
Repetition Rate	10 Hz	200 Hz
Electric Field	60 kV/cm	100 kV/cm
Stack Voltage	112 kV	175 kV
Switch Lifetime	1×10^4 pulse	1×10^5 pulse

* Work supported by the Air Force Office of Scientific Research (AFOSR) under Grant F49620-97-1-0260.

[†] Present address: GREMI, CNRS / Université d'Orleans, BP. 6759, 45067 Orleans Cedex 2, France.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE JUN 1999		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Photoconductive Switch Enhancements And Lifetime Studies For Use In Stacked Blumlein Pulsers				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Quantum Electronics, University of Texas at Dallas P.O. Box 830688, Richardson, TX 75083-0688				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.					
14. ABSTRACT Photoconductive switching of the Stacked Blumlein pulsers, developed at the University of Texas at Dallas, currently produces high power, nanosecond pulses with risetimes on the order of 200 ps. The device has a compact geometry and is commutated by a single GaAs switch triggered by a low power laser diode array. This report presents the progress toward improving the high gain switch operation and lifetime in stacked Blumlein pulsers. Feasibility of the use of amorphous diamond to enhance the switch operation and longevity is discussed Improvement in switch lifetime was demonstrated by coating the triggered face of a GaAs switch cathode with highly adhesive film of amorphous diamond.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Recently, our efforts have been directed to study and implement the broadening of the current channels in the avalanche photoconductive switch in order to improve lifetime and increase switching peak power. This is being performed by two approaches. The first is control of laser diode beam delivery to the switch, and improvements of switch contacts, pulser configuration and charging mechanism. The second approach is the study and use of amorphous diamond coating as the switch electrode coating to enhance operation and lifetime of a PCSS in stacked Blumlein pulse generators.

II. AMORPHIC DIAMOND

A. General Properties

Basic research in our laboratory has already described a conformal coating which has hardness of natural diamond and exceptionally high values of electron emissivity. Discovered at UTD in the course of BMDO supported research, it is made from graphite and laser light without catalyst, noxious byproduct, or toxic wastes. Termed amorphous ceramic diamond and later shortened to "amorphous diamond" for convenience. Deposited at room temperatures it forms a strong bond to any material onto which it is applied. Such a favorable combination of hardness, chemical bonding and an elastic modulus of 850 GPa should translate directly into an increased resistance to abrasive wear of components coated with amorphous diamond. It has been demonstrated that only a 1-3 μm coating of amorphous diamond could protect fragile substrates against erosive environments.

The experimental conditions used at UTD to deposit films of amorphous diamond have been described previously [4]. A Q-switched Nd-YAG laser was used to deliver 250 - 1400 mJ to a graphite feedstock in a UHV system at a repetition rate of 10 Hz. The beam was focused to a diameter chosen to keep the intensity on the target near $5 \times 10^{11} \text{ W cm}^{-2}$ and the graphite was moved so that each ablation occurred from a new surface. A high current discharge confined to the path of the laser-ignited plasma was used to heat and process the ion flux further.

Amorphous diamond is distinguished by the combination of its unique microstructure shown in Fig. 1 together with the mechanical properties of diamond it displays. Analytical techniques have shown it to consist of nodules of tens of nanometers in diameters that are composed of sp^3 (diamond) bonded carbon in a matrix of other carbons. The diamond character has been attested by the agreement of structural morphology, density, optical properties, Ka line energies and hardness. Nuclear reaction analysis (NRA) has proven the hydrogen content to be less than 0.5%. The nodules seem to be disordered mixtures of the cubic and the rare hexagonal polytypes of diamond that have no extensive crystalline planes along which to fracture. Such disorder creates strains that are balanced by the large surface energies available at nanometric scales. The ceramic that results from packing the nodules is surprisingly free from internal stress. Values of compressive stress measured in finished films of micron thickness are low for amorphous materials,

being 0.5 to 0.8 GPa. Since it is condensed from laser plasmas produced under conditions which are also optimal for the growth of interfacial layers, the films of amorphous diamond are strongly bonded to the substrates onto which they are condensed.

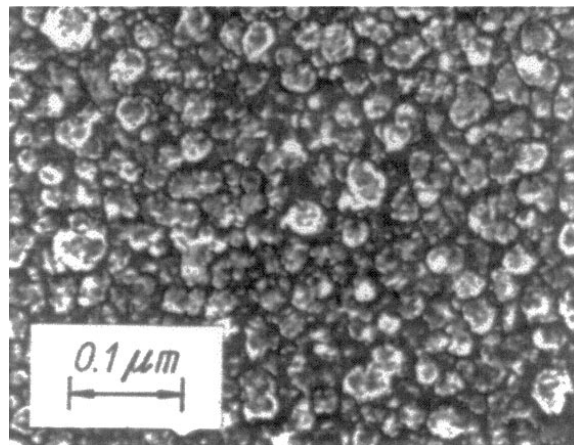


Figure 1. Diamond nodules shown by transmission electron microscopy (TEM) of a gold coated replica of a film of amorphous diamond.

B. Semiconductor Properties

Because of the potential for use in cold cathode devices and flat-panel displays, the emissivity of electrons from amorphous diamond layers is of considerable interest. The original speculation was that while the use of natural diamond as a field emitting material would encounter problems of recharging after emission because of the high resistivity of diamond, nodules of diamond in a matrix of more conductive phases of carbon might offer a viable alternative. Measurements of electron emissivity confirmed those expectations in studies comparing the performance of planar films of amorphous diamond which contained nodules of diamond with layers of defected graphite which had pointed structures of similar size to nodules.

Measurements of electron emissivity are conveniently described in terms of the Fowler-Nordheim model, which parameterizes the emitted current density, J (A cm^{-2}) as a function of the electric field strength, E (V cm^{-1}) in which the sample is immersed,

$$J = (1.54 \times 10^{-6}) \beta^2 E^2 \Phi^{-1} \exp [-(6.83 \times 10^7) \Phi^{1.5} \beta^{-1} E^{-1}] \quad (1)$$

where β is the enhancement of local electric field; S is the effective emitting area; I is the current and Φ is the work function. As can be seen, a graph of the logarithm of I/E^2 as a function of $1/E$ should be linear. Data of the type needed for comparison with the Fowler-Nordheim model has been obtained for several cathode coatings as shown in Fig. 2.

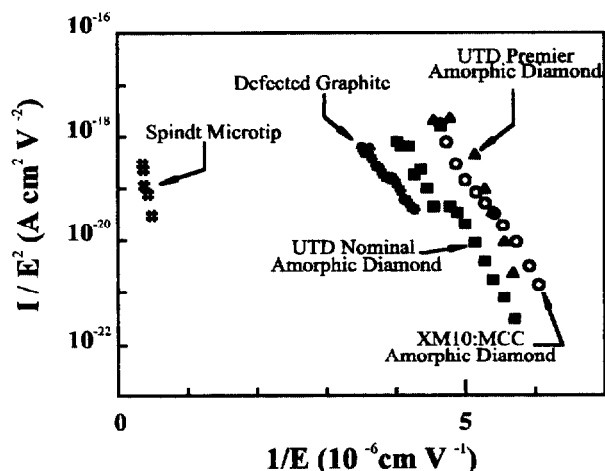


Figure 2. Plots of emission current, I per unit field strength squared, E^2 as functions of the inverse electric field strength, $1/E$ from cathodes coated with various diamond materials to facilitate comparison with the Fowler-Nordheim model.

The most striking aspect of the data of Fig. 2 is the extent to which all of the noncrystalline carbons emit a given current density at nearly an order of magnitude lower voltage that needed for a cathode of microtips. On a finer scale of inspection it can be seen that for a given voltage a cathode of amorphous diamond emits an order of magnitude more current density than does a cathode of defected graphite.

In Fig. 2 the data for "nominal" amorphous diamond is characteristic of the type of film that is usually used in mechanical studies of wear and tribology. It consists of about 75% (by volume) of diamond nodules as seen, with the balance being more conductive phases in which the nodules are embedded. However, the fraction and packing of nodules can be adjusted during deposition, and emissivity data for one option is shown by the filled triangles in Fig. 2. It seems clear that the emissivity of noncrystalline diamond films depends critically upon the packing densities of the diamond nodules and the amount of conductive phases in which they are embedded.

Deposition of thin films of amorphous diamond on both n- or p-type silicon has produced rectifying heterojunctions with highly asymmetric I-V characteristics. Regardless of the doping type and its concentration in the Si, current is rectified in the same direction with diamond layer acting as the cathode. The layered areas generate both current and voltage when illuminated acting as a source of photovoltaic power. When reversed biased, current levels from the heterojunction vary with the amount of reverse bias and the illumination. Typical I-V characteristics measured for the amorphous diamond on the p-type Si in the dark and under white light conditions are shown in Fig. 3.

The precise mechanism of heterojunction operation is not clear. Presumably, amorphous diamond conducts by a

hopping process or tunneling, while the Si conducts by an emission process. A Schottky like interface is assumed to exist due to presence of a high density of interface states. Conduction through the device is accomplished by the majority carriers through the recombination at the interface. Existence of a high density of interface states is evidenced by the direction of rectification being independent of Si impurities.

The properties discussed briefly in this section may aid longevity of the PCSS in stacked Blumlein pulsers. It is anticipated that, by depositing films of amorphous diamond near the PCSS switch contacts, the number of carriers and avalanche sites may increase improving the switch lifetime and performance.

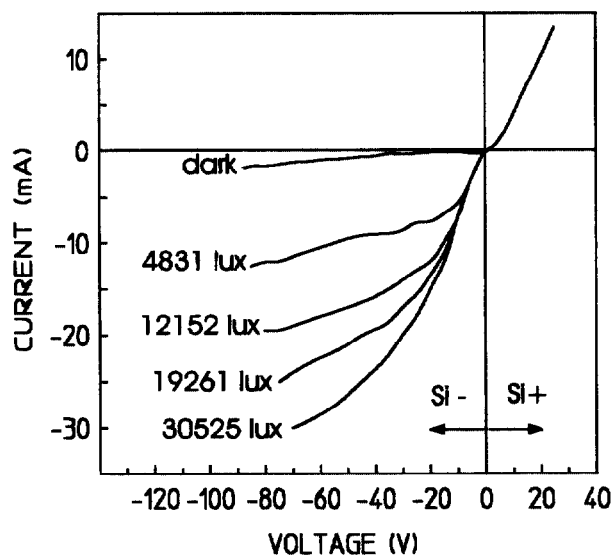


Figure 3. I-V characteristics measured for an amorphous diamond film deposited on p-type Si in the dark and under white light conditions.

III. SWITCH LIFETIME STUDIES

An isometric view of the switch/electrode configuration used in these studies is shown schematically in Fig. 4. Top copper electrode holders were connected to the base electrodes by means of several screws. The pulse forming lines from a 2-line prototype pulser were connected to the bottom of base copper electrodes which were cast in a G-10 plastic plate (2). Each switch was fabricated from one half of a semi-insulating LEC grown GaAs wafer with a diameter and thickness of 5 cm and 0.5 mm, respectively. It was held in place by means of two copper holders screwed to the electrodes. Activation of switch was performed by collimating and focusing the LD-220 laser diode array beam in two straight lines across the switch gap from cathode to anode. A novel beam scanning system was used to scan the focused laser beam across the switch width and thereby changing the location of the current filament for each cycle of commutation.

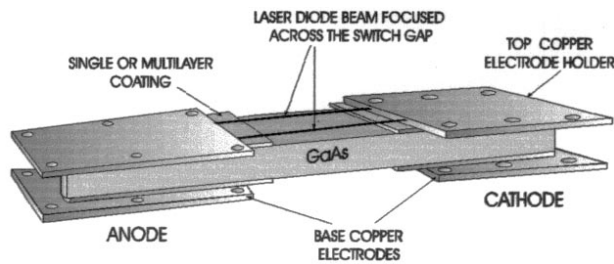


Figure 4. Schematic drawing of the switch/electrode configuration used in these studies.

For the sake of consistency, we placed layers of Kapton insulator between the switch and the base electrode to restrict the current path through the top electrodes and so only switch front contacting the top electrodes was affected and damaged. In this configuration, we performed the switch longevity experiment with a bare GaAs switch with no contacts. The switch commutated the pulser at 72 MW (1.2 kA current) for 5×10^3 shots after which it failed. A photograph of this switch after completing the test is shown in Fig. 5(a) for reference. The switch damage is at the limit of the copper plate electrodes not shown in the figure. The damage line shown at the bottom of Fig. 5(a) corresponds to the cathode side. More damage is seen at the cathode electrode contact.

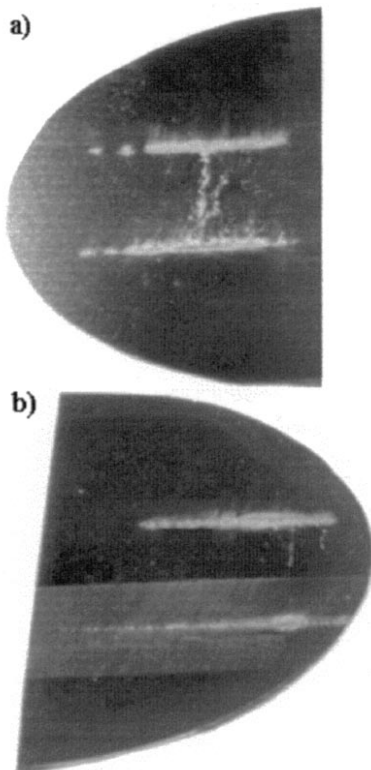


Figure 5. Photographs showing (a) a GaAs switch with no contact (b) a GaAs switch with the amorphous diamond coating, after 5×10^3 cycle of commutation at 72 MW.

In this work, we also studied the lifetime of a GaAs switch with a 1-cm strip of amorphous diamond deposited on the switch at the cathode location. The film thickness was 600 nm. The switch assembly permitted a switch gap of 12 mm with diamond strip extended about 5 mm into the gap. The switch was tested under similar conditions of experiment as described earlier. The switch lifetime was found to be 1×10^4 commutation cycles. Figure 5 (b) presents a photograph of the switch after 5×10^3 shots. The switch damage is located at the limit of the copper plate electrodes not shown. The damage line shown at the bottom of Fig. 5(b) corresponds to the cathode side and shows less damage as compared to the anode damage line shown at the top of this figure. With the application of amorphous diamond, not only the switch lifetime was increased but also the damage at the cathode contact was found to be less than that found for the anode contact. This indicated that diamond coating protected and hardened the cathode side.

In experiments where the switch had no diamond coating, the majority of the time, a single current filament commutated the switch. The filament was initiated near the cathode and followed, approximately, one of the laser beams to the anode. Multiple branching was rarely seen [2]. In the case of switch with the diamond coating, the multiple branching was observed more often indicating an increase of pre-avalanche sites.

IV. REFERENCES

- [1] F. Davanloo, D.L. Borovina, J.L. Koriath, R.K. Krause, C.B. Collins, F.J. Agee, J.P. Hull, J.S.H. Schoenberg and L.E. Kingsley, "High Power, Sub-Nanosecond Rising Waveforms Created by the Stacked Blumlein Pulsers," in *Ultra-Wide-Band, Short-Pulse Electromagnetics 3*, C.E. Baum, L. Carin and A.P. Stone, Eds., New York: Plenum Press, 1997, pp. 31-38.
- [2] F. Davanloo, C.B. Collins, and F.J. Agee, "High Power, Repetitive-Stacked Blumlein Pulsers Commutated by a Single Switching Element," *IEEE Trans. Plasma Sciences*, Vol. 26, pp. 1463-1475, Oct. 1998.
- [3] F.J. Zutavern, G.M. Loubriel, W.D. Helgeson, M.W. O'Malley, R.R. Gallegos, A.G. Baca, T.A. Plut, and H.P. Hjalmarson, "Fiber-optic Control of Current Filaments in High Gain Photoconductive Semiconductor Switches," in *Conference Record of the 1994 Twenty-First Power Modulator Symposium*, 1994, p. 116.
- [4] F. Davanloo, H. Park and C.B. Collins, "Protective Coatings of Nanophase Diamond Deposited Directly on Stainless Steel Substrates," *J. Mat. Res.*, vol. 11, pp. 2042-2050, Aug. 1996.